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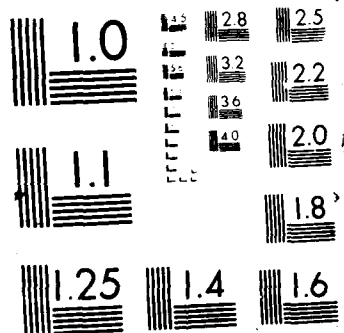
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IMPROVEMENTS IN TECHNIQUES OF MICROWAVE THERMOGRAPHY

ANNUAL REPORT

ALAN H. BARRETT

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Research Laboratory of Electronics
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) During the period 15 November 1982 to 15 November 1983 our research has been concentrated in two areas: (1) the design, construction, and testing of a reflection-compensating radiometer, and (2) a theoretical investigation of the variation of microwave penetration depth in human tissue as a function of the aperture size of the contact antenna. The radiometer operates at 1.4 GHz in the unbalanced mode and gives the reflection coefficient and the microwave temperature of the emitter corrected for reflections. The penetration depth of microwaves in body tissue depends		

20. Abstract (continued)

critically on the aperture size and is significantly less than the penetration depth computed from the usual plane wave (or far field) approximation.

depth is a factor of the aperture size



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8	Penetration depth in breast tissue as a function of aperture size.

BODY OF THE REPORT

During the period 15 November 1982 to 15 November 1983 work was concentrated in two areas: (1) design, construction and testing of a reflection-compensating radiometer, and (2) an investigation of the interplay between aperture size and penetration depth using near-field electromagnetic theory applied to apertures in contact with human tissue. The results of this research is summarized below.

Reflection-Compensating Radiometer

During the past year of funding we have developed a radiometer, operating at 1.4 GHz, capable of determining both the tissue temperature and the emissivity of the tissue. Designs for such reflection-compensating radiometers have been proposed by several groups^{1,2,3} and we initially followed their designs closely. Basically two measurements must be made to determine both the temperature and emissivity and this is accomplished by measuring (1) the emission from the subject and (2) the emission from the subject plus the reflected power from the subject when a small amount of power is directed at the subject. A block diagram of the final system is shown in Figure 1. The system is calibrated by taking two measurements with the calibration switch on the short, one with the noise tube on and one with the noise tube off. Two measurements are then made with the calibration switch on the antenna, again one with the noise tube on and one with the noise tube off. These data are then used to compute the reflection coefficient and the microwave temperature incident on the antenna as shown in Figure 2. The calibration and measurement procedures are controlled by the microprocessor, which also controls the Dicke switch, and the results are displayed on a video terminal.

BLOCK DIAGRAM OF RADIOMETER

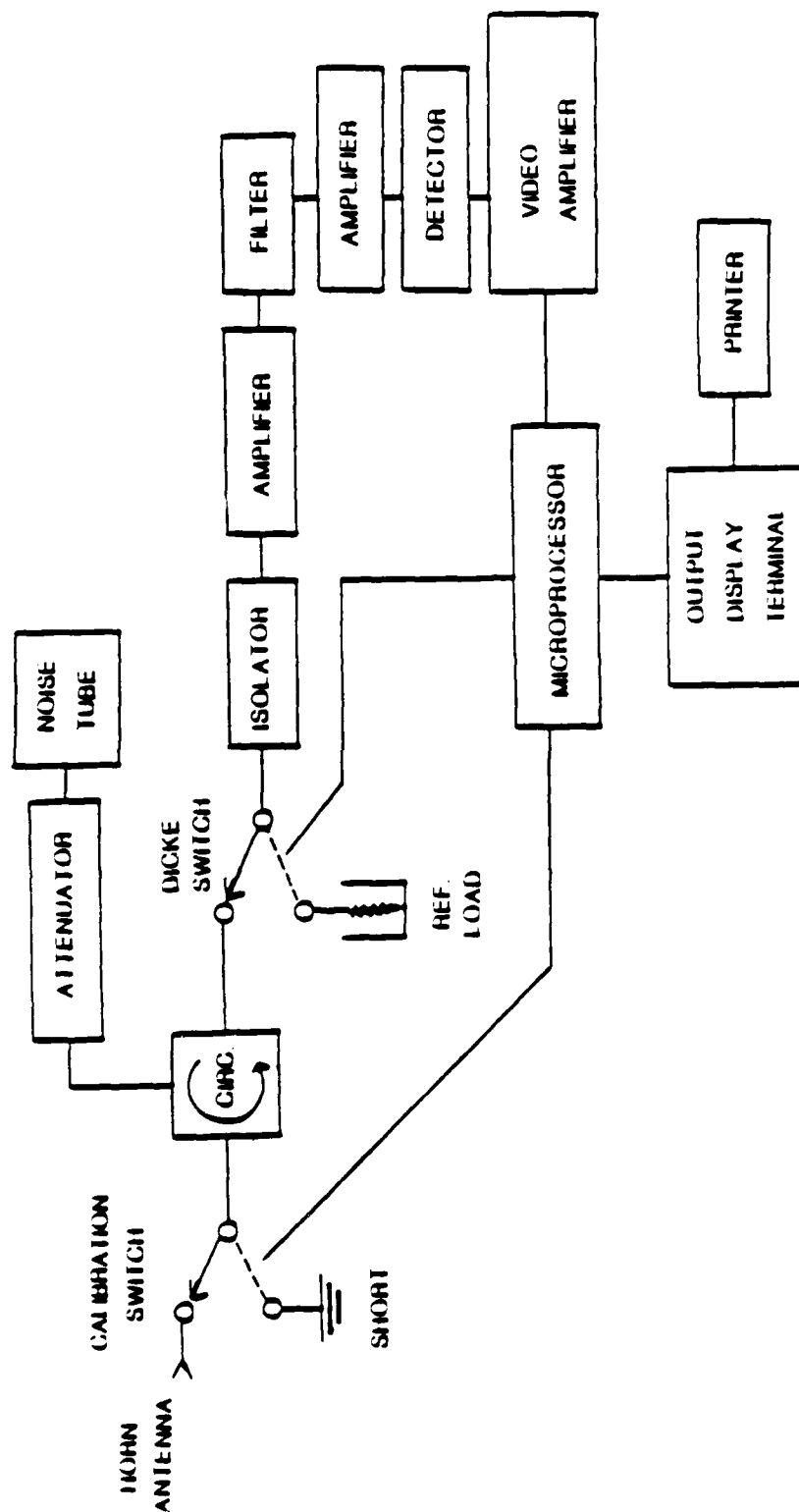
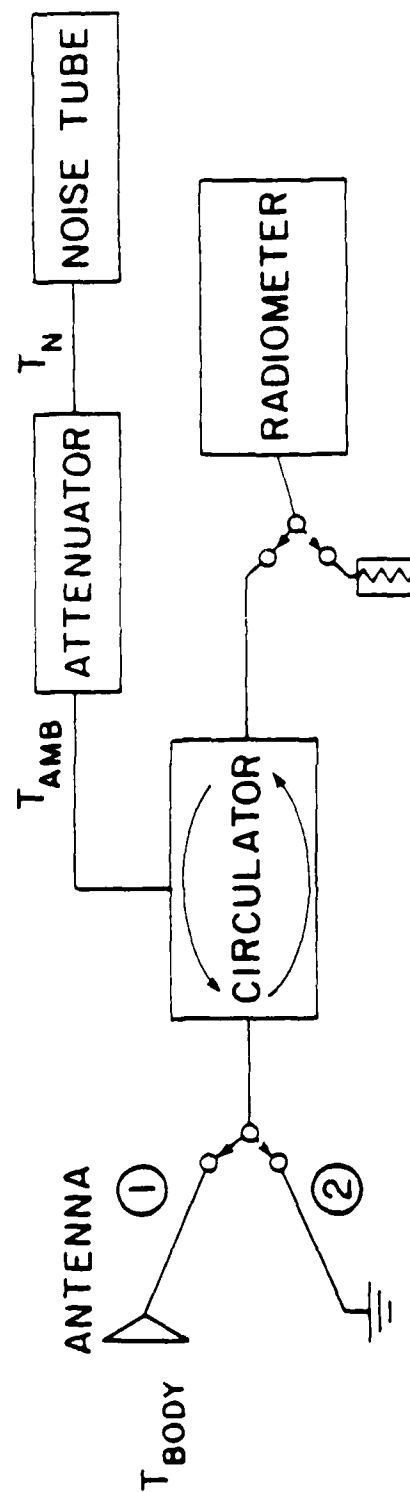


Figure 1

REFLECTION COMPENSATING RADIOMETER



ΔT 'S ARE MEASURED RADIOMETRIC READINGS

$$\rho = (\Delta T_A - \Delta T_B) / (\Delta T_C - \Delta T_D)$$

$$T_{BODY} = [(\Delta T_A - \Delta T_B) / (1 - \rho)] + T_{AMB}$$

NOISE TUBE SWITCH POSITION

ΔT_A	ON	1
ΔT_B	OFF	1
ΔT_C	ON	2
ΔT_D	OFF	2

Figure 2

The system differs from many previously proposed in that it operates in an unbalanced mode at all times. Other systems have incorporated a servo loop to drive one of the observed signals to zero. We found this inconvenient because of the minimum step available with a motor-driven attenuator and the time delay in making an observation as the attenuator was driven toward balance. Our present radiometer has sufficient gain stability that operation in an unbalanced mode is not detrimental.

The radiometer operates over the 400 MHz band from 1.2 to 1.6 GHz and experiences some interference from the radar at Logan Airport. This is not too surprising since the radiometer, in its present form, is a bench model and has not been packaged in any way. Packaging the system, currently underway, may help the interference problem but certainly will not eliminate the radar problem from entering the antenna. A significant amount enters the antenna since we notice a major reduction in interference when the antenna is replaced by a heated matched load. However, the integration of the radiometer is approximately 3 seconds and the rotation rate of the antenna is 12 seconds so the radar interference has not been too severe to prevent us from operating with some precaution. When looking at a resistive load, the radiometer routinely determines temperature to better than 0.1 C and the reflection coefficient to better than 0.002. When looking at an antenna directed toward absorbing material with an air gap between the antenna and absorber, the performance deteriorates by a factor of 2-3, presumably due to radar interference. This is not regarded as too serious at the present time.

Aperture Size and Penetration Depth

Many investigations of microwave thermography have utilized open-end, dielectric-filled, waveguides as the antenna, coupling the body emission to the radiometer. Since the penetration depth is greater for longer wavelengths most thermographic studies have been done in the 1-6 GHz range. However, this relatively low frequency range requires unduly large waveguide apertures thereby destroying spatial resolution. By filling the guide with a dielectric one effectively decreases the wavelength in the medium and permits the propagation of 1-6 GHz radiation in a waveguide of reduced dimensions. Furthermore, the impedance match of the antenna to the body, necessary for optimum power transfer, is improved by the addition of the dielectric.

However, estimates of the penetration depth using the usual plane wave formula are overly optimistic and in need of drastic revision when applied to a waveguide aperture in direct contact with human tissue. The reason is not difficult to envision. The plane wave case is applicable only when the distance from the aperture to the subject is large so that waves emanating from the aperture may be approximated as plane waves at the subject. This is clearly not the case when the antenna aperture is in contact with the subject.

Even the definition of penetration depth is not applicable for contact antennas because the electromagnetic fields do not fall off exponentially with increasing distance from the aperture until the far-field (plane wave) region is reached. Nevertheless, one can define the penetration depth as the distance where the power is e^{-1} or 0.368 (4.34 db) of the value at the surface. This

distance will depend on the angle with respect to the axis of the aperture because the surface of constant power is not spherical.

In Figure 3 we show the results of our calculations of the on-axis penetration depth as a function of aperture size, measured in wavelengths in the medium, for several frequencies commonly used in microwave thermography. The calculations assumed a skin thickness of 1.5 mm overlying breast tissue and that only the TE_{10} mode was excited in the antenna even though the dimensions were large enough to permit other modes to propagate. Similar computations for a single aperture size have been done by Audet et al⁴ for 3 and 9 GHz and by Edenhofer et al⁵ for 1 GHz. Their conclusion, like ours, is that the penetration depth strongly depends on the characteristics of the antenna and that plane wave penetration depth grossly overestimates the actual case unless the aperture dimensions exceed one wavelength or the tissue being examined is very lossy, i.e. high in water content. For example, the plane wave penetration depth would be at least two times the values given in Figure 3 for $a/\lambda_m = 1$. Thus one sees how the penetration depth is seriously compromised for aperture dimension less than a wavelength in size.

We have constructed a series of three antennas at each of two frequencies, 1.4 and 3 GHz, which we plan to use to experimentally determine both the penetration depth and spatial resolution. The thermal source will be a small glass bulb, filled with water, fitted with a heater and thermistor for temperature control and measurement, and embedded in slabs of simulated tissue. Such a device will be useful for determining the properties of future antennas also.

PENETRATION DEPTH IN BREAST TISSUE AS A FUNCTION OF APERTURE SIZE

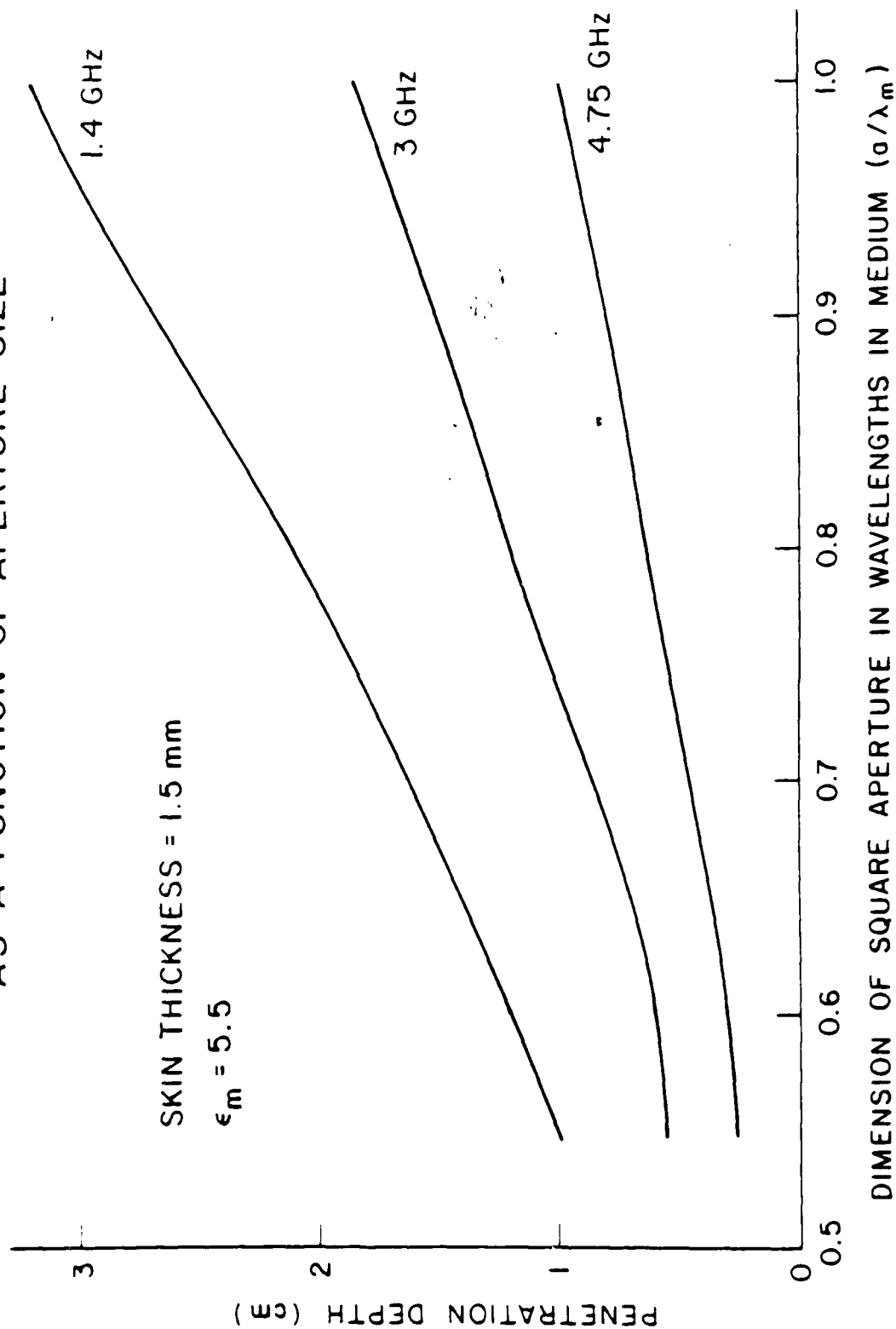


Figure 3

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